An experimental study of transverse and longitudinal wakefields driven by a self-modulating proton bunch

Marlene Turner for the AWAKE collaboration
Outline

● Introduction to the AWAKE Experiment

● Wakefield Measurements
  ○ Concept, Challenges

● Results

● Conclusion & Summary
Introduction to AWAKE

- AWAKE stands for: **Advanced (Proton Driven Plasma) WAKEfield Experiment.**

- AWAKE is a **R&D project** to study proton driven plasma wakefields at CERN.

- **Final Goal:** Design high quality & high energy electron accelerator.

**Why protons?**

Highly-relativistic proton bunches (e.g. at CERN) have the potential to drive wakefields that can accelerate a witness bunch to TeV energies in a single plasma.

Seeded Self-Modulation

proton bunch density in the beginning of the plasma

proton bunch density after 10 m of plasma

resonant wakefield excitation

AWAKE Run 1, Phase 1 (2016, 2017)

all simulations performed with LCODE (2D cylindrical, quasistatic)

M. Turner
for the AWAKE collaboration

AWAKE CERN
Seeded Self-Modulation

proton bunch density in the beginning of the plasma

proton bunch density after 10 m of plasma

resonant wakefield excitation

as discussed in the plenary session on Monday (Proton Bunch Self-Modulation and Electron Acceleration in AWAKE by P. Muggli, 12:00)

streak camera image of the self-modulated proton bunch

AWAKE Run 1, Phase 1 (2016, 2017)

M. Turner for the AWAKE collaboration

AWAKE Collaboration Phys. Rev. Lett. 122, 054802
M. Turner et al. (AWAKE Collaboration); Phys. Rev. Lett. 122, 054801

proton bunch self-modulation and resulting wakefield amplitude growth has been experimentally demonstrated:

AWAKE Collaboration Phys. Rev. Lett. 122, 054802
M. Turner et al. (AWAKE Collaboration); Phys. Rev. Lett. 122, 054801
electron delay ~100-800 ps wrt to the ionizing laser pulse

oblique electron injection:

1) Short plasma density ramp at the entrance of the plasma
   ⇒ change of wakefield phase
2) During the SSM the proton bunch distribution evolves
Electron Acceleration

Electrons off (protons & high power laser on)

Electrons on (protons & high power laser on)

- electron acceleration in wakefields driven by a self-modulating proton bunch
- finite electron energy spread
- GeV acceleration (up to ~2 GeV, from ~20 MeV)

AWAKE Run 1, Phase 2 (2018)

electron delay ~100-800 ps wrt to the ionizing laser pulse

oblique electron injection:


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Measurement Concept

wakefields amplitudes along the 10m plasma in AWAKE

How to measure?

- accelerate electrons
- all simulations performed with LCODE (2D cylindrical, quasistatic)

$W_z$ at $r = 0$ and $\xi = -200$ps

growth

seed at center

along the plasma
Measurement Concept

wakefields amplitudes along the 10m plasma in AWAKE

How to measure?

accelerate electrons

measure radial proton bunch distribution

all simulations performed with LCODE (2D cylindrical, quasistatic)

$W_z$ at $r = 0$ and $\xi = -200\text{ps}$

$W_r$ at $r = \sigma_r$ and $\xi_{\text{max}}$

along the plasma

measured range

measured range

initial seed

transverse

longitudinal

seed at center

seed at center

$\eta_{\text{pe}} = 2 \times 10^{14} \text{ cm}^{-3}$

initial seed

growth

growth

laser pulse

electrons

protons

How to measure?
Seed Position Scan
longitudinal wakefields

Preliminary

waterfall plot of the measured electron energy spectrum as a function of the laser pulse seed position

change laser pulse and electron bunch position together
Seed Position Scan
longitudinal wakefields

change laser pulse and electron bunch position together

waterfall plot of the measured electron energy spectrum as a function of the laser pulse seed position

identify the peak energy

integral of $W_z$ (over 10 m)

measurement

measured peak electron energy follows the same shape as the integrated longitudinal wakefield amplitude!
Seed Position Scan
transverse wakefields

Measurement setup:

Seed Position Scan
transverse wakefields

Measurement setup:

![Diagram showing measurement setup with plasma, protons, and imaging stations.]

- Measure maximum radius of defocused protons

Maximum radius of the defocused protons follows the same shape as the integrated (0-4m) transverse wakefield amplitude!

- Preliminary measurement:
  - \( \int_{0m}^{4m} W_r \, dz \)

Radial proton bunch density during self-modulation:

- Counts / bin

Electron Delay Scan

longitudinal wakefields

change the delay (0-800 ps) between the electron bunch and the laser pulse:

measured peak electron energy follows the same shape as the integrated longitudinal wakefield amplitude!
Ongoing studies...

electron acceleration dynamics

electron dynamics complicated as wakefields phase is evolving along the plasma due to the self-modulation process

defocused proton trajectories

where do protons exit? which ones are the outermost on the screen?
Conclusions & Summary

- AWAKE is a **proton driven** plasma wakefield experiment.
- The **self-modulating** proton bunch resonantly drives wakefields in the 10 m long plasma.
- We probe and study the **longitudinal wakefields** by externally injecting electrons.
- We probe and study the **transverse wakefields** by looking at the transverse proton bunch distribution downstream the plasma.
- The measured **dependencies** (on seed position and electron delay) scale with the simulated wakefield amplitudes, confirming the expected physics scalings.